Curling Under Different Environmental Variations As Monitored In A Single Concrete Slab

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Abstract

More than five months of sensor response monitoring was conducted on a single Portland Cement Concrete (PCC) slab test at the National Airport Pavement Test Facility (NAPTF). Reliable data for relative humidity at different depths within the slab have been retrieved. The monitored data also included temperature, horizontal and vertical displacements, and strains at different locations. The completely wet curing method kept the slab flat within that period. However, when the wet curing stopped, the maximum slab curling reached a very high level. Correlations between the horizontal and vertical displacements, and the correlation between displacements and temperature and relative humidity variations are analyzed. The analysis of correlations between slab curling and concrete strains are also presented. Significant findings are obtained and summarized.

Introduction

A single slab test is the third full-scale PCC slab test conducted at the National Airport Pavement Test Facility (NAPTF). Many lessons have been learned in the previous two tests. First, by virtue of an unexpected failure mode, many top-down corner cracks were observed in the tests conducted at the FAA, NAPTF, in 2000 defined as the construction cycle one (CC1) test (Guo, Hayhoe & Brill, 2001). When the CC1 tests were planned, the desired range of pass-to-failure number (1000 to 10,000) was selected. Based on the existing design specifications, relatively thin slabs with thicknesses between 22.9 to 28 cm (9 to 11 inches) were constructed to reach the target pass number for a concrete flexural strength close to or higher than 5.52 MPa (800 psi). Since the pavements would be built in an in-door environment, both temperature and moisture variations were estimated to be much less than the pavement under an out-door environment. However, after the pavements were constructed, the slab curling measured by the falling weight deflectometer (FWD) was found to be much higher than expected. The significant slab curling was thought responsible for the top-down cracking being more critical than the bottom-up cracking in the slabs. Many questions were discussed in the FAA working group meetings since 2000. Some of them are listed as below:

(1) Since the maximum recorded temperature difference between the slab surface and the bottom in CC1 was always close to or lower than $3^{\circ}C$ ($5\ ^{\circ}F$), what is the major contributor causing the significant curling in the indoor environment?
Can the curling be significantly reduced by using a different concrete mix?
Can the curling be significantly reduced by applying a longer wet curing period?

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Can the use of 4.52 by 4.52 meter (15 by 15 ft) slabs lead to the bottom-up cracking being more critical than the top-down cracking which was observed in the 6.1 by 6.1 meter (20 by 20 ft) slabs in the CC1 tests?

To answer the above questions, a second test pavement defined as "Test Strip" was constructed in November 2001 at the NAPTF to investigate the effect of different concrete mixes and the effects of slab size and curing method. It has been quantitatively verified that if all conditions are the same, a larger slab leads to larger curling. Therefore, 4.52 by 4.52 meter (15 by 15 ft) slabs were selected for the tests conducted in 2004 that are defined as the CC2 tests. The detailed discussion related to the concrete mix and curing method may be found in a reference by McQueen, Rapol & Flynn, 2002. During the test, the five saw-cut joint formations were monitored, and the detailed behavior of the slab in-plane and out-of-plane deformations, and strains in the transverse and longitudinal directions have been recorded. However, several problems still needed to be clarified after the test strip testing was completed.

First, only detailed temperature-time histories were obtained during the test strip project. They have been analyzed based on the first saw-cut joint formation observed in the first month after the concrete placement. The joint formation was mainly caused by the recorded high temperature difference rather than the moisture gradient since the slabs were fully wet under routine watering for the entire month. All other joint formations seemed to be mainly due to shrinkage caused by moisture change in the concrete after watering was stopped and the wet burlap was removed. However, no moisture information was directly measured in the test strip project. If we intend to separate the two effects, temperature and moisture, the direct moisture variation information is necessary.

Second, the concrete flexural strengths for both mixtures were still very high, although great efforts had been made to reduce the flexural strength by trying different mixes. Small-batch mixes with different levels of fly ash replacement were therefore tried. A mix with 60% fly-ash proportion in the cementitious mix was selected as being suitable for further full-scale testing.

Third, five joints in the test strip were formed at different times and each of them provided different effects on the curling of each slab. Therefore, the curling of the slabs was influenced not only by the environmental variations combined with interface conditions between the slab and subbase, but also by the joint conditions. Also, only the overall horizontal displacements were measured in the test strip and it was difficult to find the relationship between the horizontal and vertical displacements of a single slab. Performing a single slab test would simplify the testing conditions, and the investigation could be conducted without the inherent response of the slab being obscured by joint effects.

Using the 60% fly ash mix, a 4.52 by 4.52 meter (15 by 15 ft) test slab was constructed at the beginning of June, 2003 on the surface of a cracked slab from the CC1 test, figure 1. One full month of curing was executed by watering the burlap covered slab routinely to keep the slab completely wet. Then three different testing procedures were executed. First, during three and a half months of drying, under the indoor natural environment condition, all sensors were monitored. At the end of that period, the measured average upward corner curling reached almost 5.1 mm (200 mils). Static plate load tests up to 13625 kg (30,000 lbs) with intervals of 2270 kg (5,000 lbs) were conducted at the end of this period to measure the displacements and strains of the curled slab. The second procedure consisted of covering the slab with burlap and routinely watering the slab surface for about two months. At the end of this period, the measured average corner curling was stable and had dropped to 1.5 to 2 mm (60 to 80 mils). Then similar static plate load tests up to 18160 kg (40,000 lbs) were again conducted to investigate the slab response under a different degree of curling. Different plate sizes with diameter of 45.7, 30.5 and 15.25 cm (18, 12 and 6 inches) were also used to find their effect on the critical strain and displacement. The third testing period started after the second static tests were completed. The slab was dried again under natural conditions

Results from the first two test slab testing periods, including the long term variation of horizontal and vertical displacements and strains, are presented in this paper. Comparisons between the curling predicted by a simple model and the one measured in the test are also presented and discussed.

Hc = 27.9 cm (11 inches), New P501

$H_{ExistPCC}$ = 24.8 cm (9.75 inches), cracked slab, P501

H_{Sub1} = 14.9 cm (5.875 inches), econoconcrete, P306

H_{Sub2} = 21.9 cm (8.625 inches), granular, P154

Subgrade, CBR = 7 to 8

Figure 1. A 4.52 by 4.52 meter (15 by 15 ft) Slab Built on a Cracked 6.1 by 6.1 meter (20 by 20 ft) Slab

Corner and Edge Curling Measurements

A 28 cm (11 inch) thick, 4.57 by 4.57 meter (15 by 15 feet) slab was built on the surface of a 24 cm (9.5 inch) thick, 6.1 by 6.1 meter (20 by 20 feet) slab that was a portion of the CC1 test pavements constructed in April, 1999 and tested in the spring of 2000. Under the 24 cm (9.5 inch) slab was a layer of 15 cm (5.875 inch) econocrete (material P-306) and 22 cm (8.625 inch) granular subbase (material P-154), both materials following the requirements in AC 150/5370-10A. The subgrade was about 3.7 meter (12 feet) depth of clay having a California Bearing Ratio (CBR) 7 to 8. Samples from different concrete mixes were tested in a laboratory (Flynn,

2003) to determine the final mix. A 60% fly ash cementitious mix was selected in casting the test slab.

Sensors installed in the slab included five vertical displacement transducers (VD) at the four corners and one edge. Four horizontal displacement sensors were installed at the center of the west and east sides of the slab. Two sets of temperature and relative humidity sensors were each placed at three depths within the slab thickness. Three sets of strain gage sensors were each installed in the upper, middle and lower positions within the slab thickness. The detailed plan view and sensor locations are presented in Figure 2. All sensors under the variation of the natural indoor environment were continuously monitored and the results are presented and discussed herein.

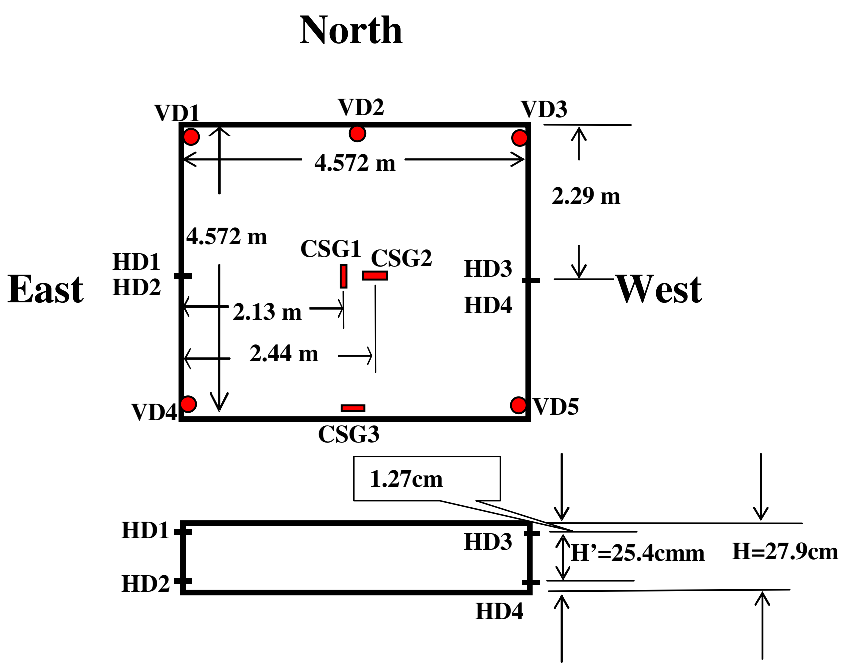


Figure 2. Plan and Elevation Views of the Test Slab and Sensor Locations

The time histories of the temperature and relative humidity are presented in Figures 3 and 4. Figure 3 does not show clear peak temperatures for the few days following the concrete placement on June 2, 2003. This indicates that the 60% fly ash mixture in the single test slab significantly reduced the heat released from the early age hydration. After about a two-month stable period, in July and August, 2003, the concrete temperature in the slab started to decrease. The upper temperature sensor experienced the highest daily variation, and the temperature gradient $(T_{surface}-T_{Bottom})/H_{Slab}$ remained at a low level, compared to typical field conditions, during the monitoring period.

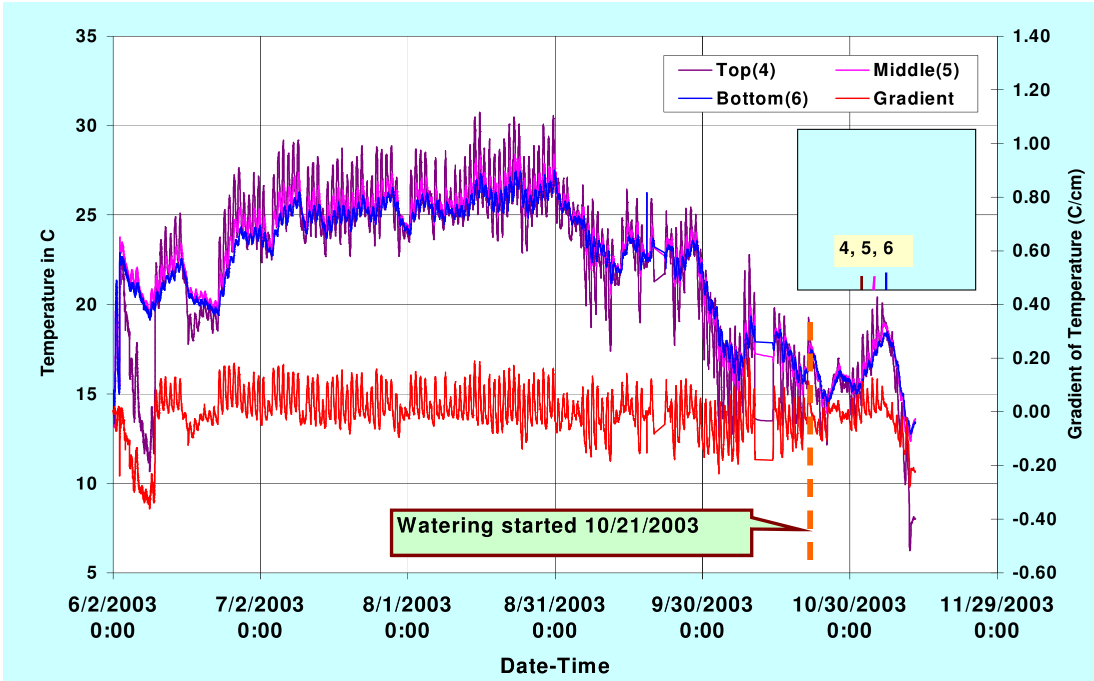


Figure 3. Five-Month Temperature Records for the Single Slab Test

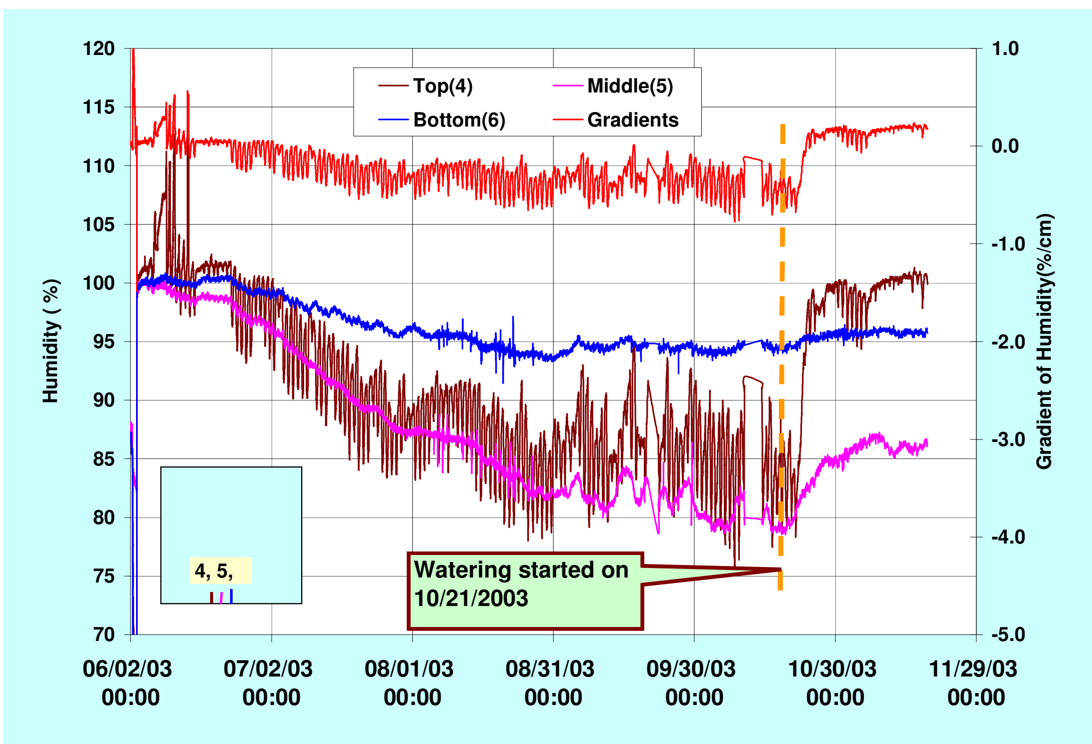


Figure 4. Five-Month Relative Humidity Records for the Single Slab Test

The relative humidity readings were always close to 100% during the wet curing period since the slab was always kept totally wet. After the burlap was removed on June 30, 2003, the relative humidity of the upper and middle sensors, 1.27 cm (0.5 inches) and 14 cm (5.5 inches) from the slab surface respectively, continuously decreased. Though the average values were close to each other, the daily variations detected by the upper relative humidity sensors were much higher than those of the middle sensors. The relative humidity variation measured by the sensors at 1.27 cm (0.5 inches) from the slab bottom were the lowest. About two months following the wet curing period, the average relative humidity became stable. However, after the slab surface was watered routinely starting October 21, 2003, the relative humidity measured by the upper sensors quickly jumped from an average of 82% back to almost 100% in about two days. The middle sensor readings moved from 82% to 85% in about ten days. The lower sensor readings had only very limited change (about 1%) after the slab was watered.

Figure 5 presents more than six months of data from monitoring the vertical displacement sensors. Unfortunately the VD3 sensor had some problems and was disconnected during the wet curing period. No VD3 results are presented in this paper.

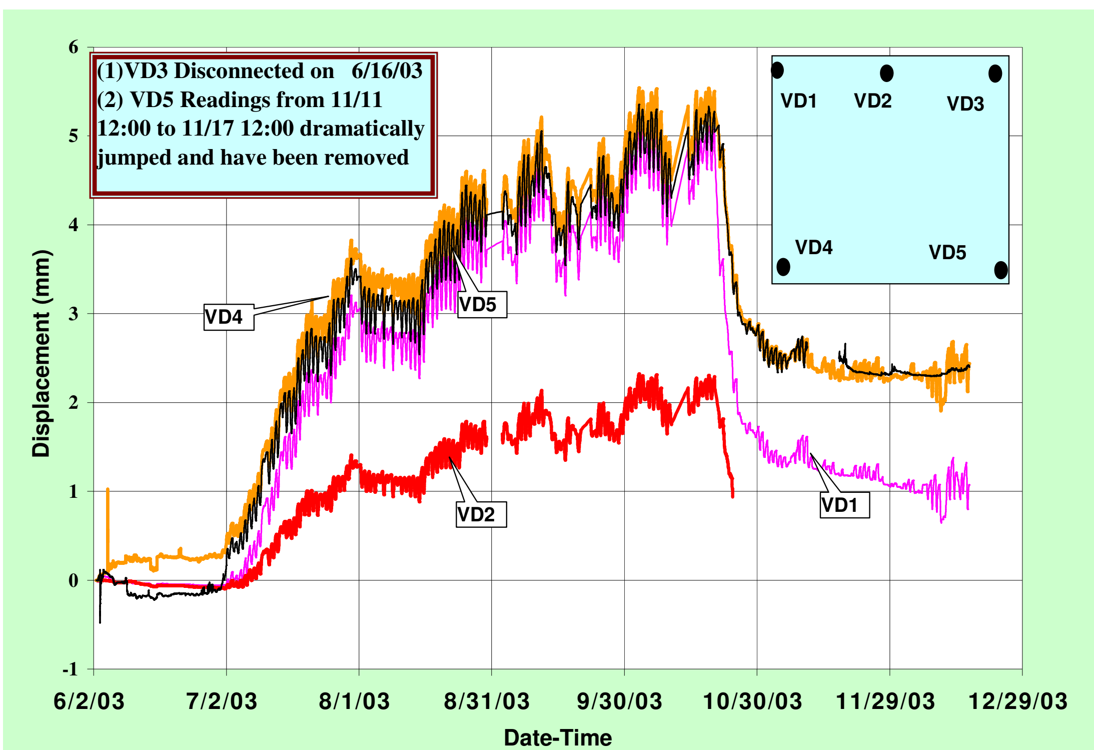


Figure 5. Measured Slab Curling at Corners and at Edge

Summary of findings.

(1) All three corner sensors and one edge sensor verified that the slab was not curled during the first month wet curing period. All displacements measured on July 2 were almost zero except for 0.3 mm (11 mils) measured at VD4.

(2) The three corner sensors recorded similar vertical displacements for more than four months until the slab was watered on October 21, 2003. After that the two displacement sensors on the south side (VD4 and VD5) varied similarly, and VD1 on the north side showed more slab relaxation curling than did VD4 and VD5. The difference between VD4, VD5 and VD1 probably was due to non-uniform water absorption by the slab.

(3) In the first month after the wet curing, the average corner curling quickly increased to 3.4 mm (134 mils) corresponding to a similarly large change of relative humidity, Figure 4. The average gradient of the relative humidity dropped to about 0.3 % / cm. However, the variations of both daily averages and temperature gradients, during the same period, were very limited. The data indicates that the slab curling was more related to relative humidity variations than to temperature variations.

(4) The corner curling continuously developed at a lower rate in August corresponding to the reduced variation rate of the recorded daily average relative humidity. The average temperature variations in August were still limited.

(5) During the thirty days that followed (September), the daily average of slab curling kept stable, but the daily curling variations were still significant. During the same period, the daily average of the relative humidity remained stable but its daily variations were even higher. The above observations also indicate good correlation between corner curling and relative humidity, for both daily averages and daily variations.

Horizontal Slab Movements

Figure 6 illustrates the relative horizontal movements at the top and bottom of the slab. The locations of sensors are presented in Figure 2. Within the wet curing period, the readings are very limited. After the watering stopped and the wet burlap was removed on June 30, 2003, the top and bottom relative movement developed at a different rate: the top reached 1.53 mm(60 mils) and the bottom reached 0.67 mm (26 mils) in a month. After August 1, 2003, the two horizontal relative movements behaved differently. The top relative movement (HD1+HD3) continuously increased until the slab started to be watered on October 21, 2003. The bottom one (HD2+HD4) kept relatively stable within the same period. The average value of top and bottom relative movements (HD1+HD2+HD3+HD4)/2 may be defined as an index corresponding to the slab in-plane movement. And the difference of the top and bottom relative movements (HD1+HD3-HD2-HD4) may be defined as an index corresponding to the out-of-plane slab movement. The "average" curve in Figure 6 indicates that most slab in-plane movement was completed in about one month after the wet curing. Then the slab in-plane movement became very limited and stable. However, the "difference" curve in Figure 6 shows that slab out-of-plane (bending) movements continuously developed though the rate in the beginning was higher than later. Comparing the "difference" curve in Figure 6 with the corner curling curves in Figure 5 indicates that they are well correlated.

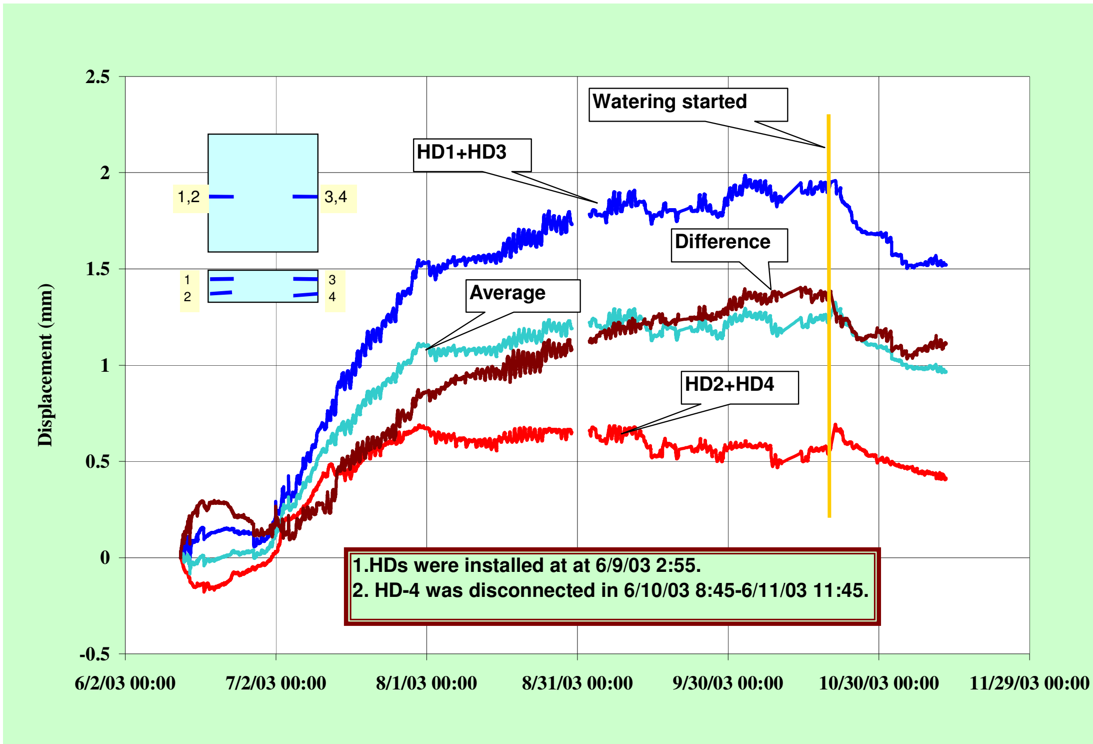
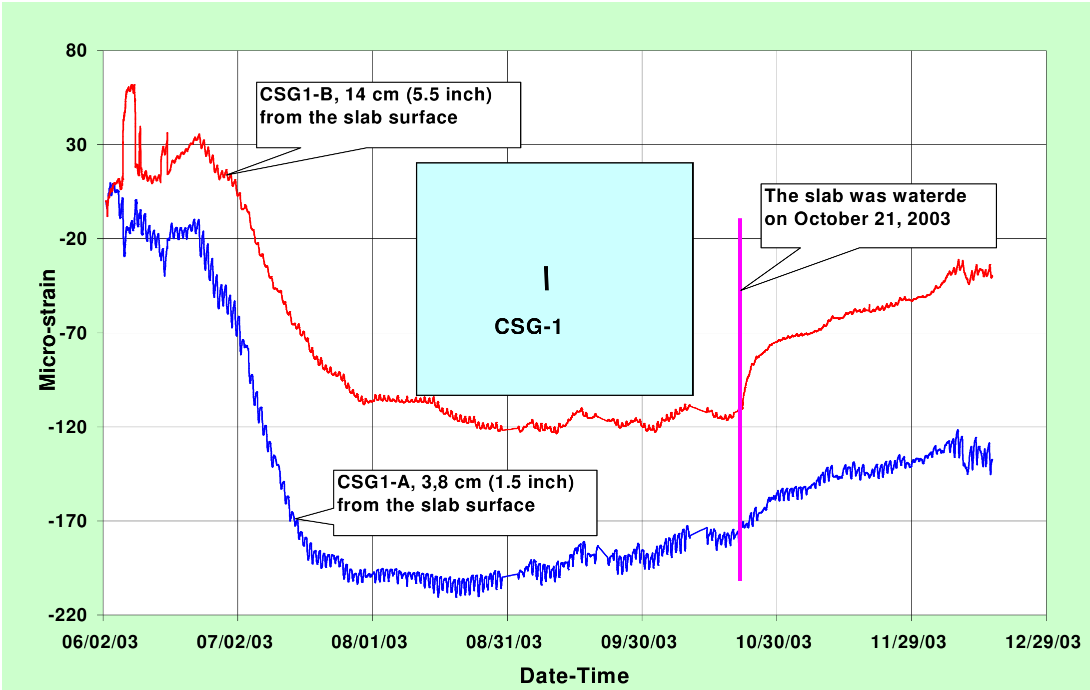
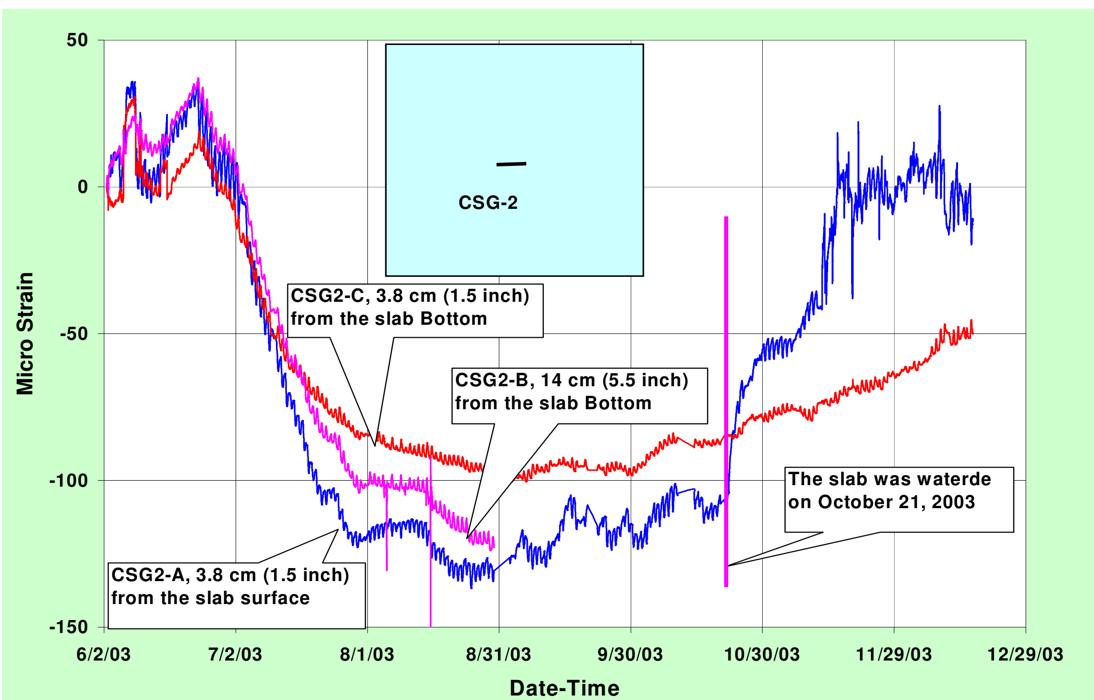


Figure 6. Measured Horizontal Displacements



(a) In transverse direction



(b) In longitudinal direction

Figure 7. Strain Time Histories at the Slab Center

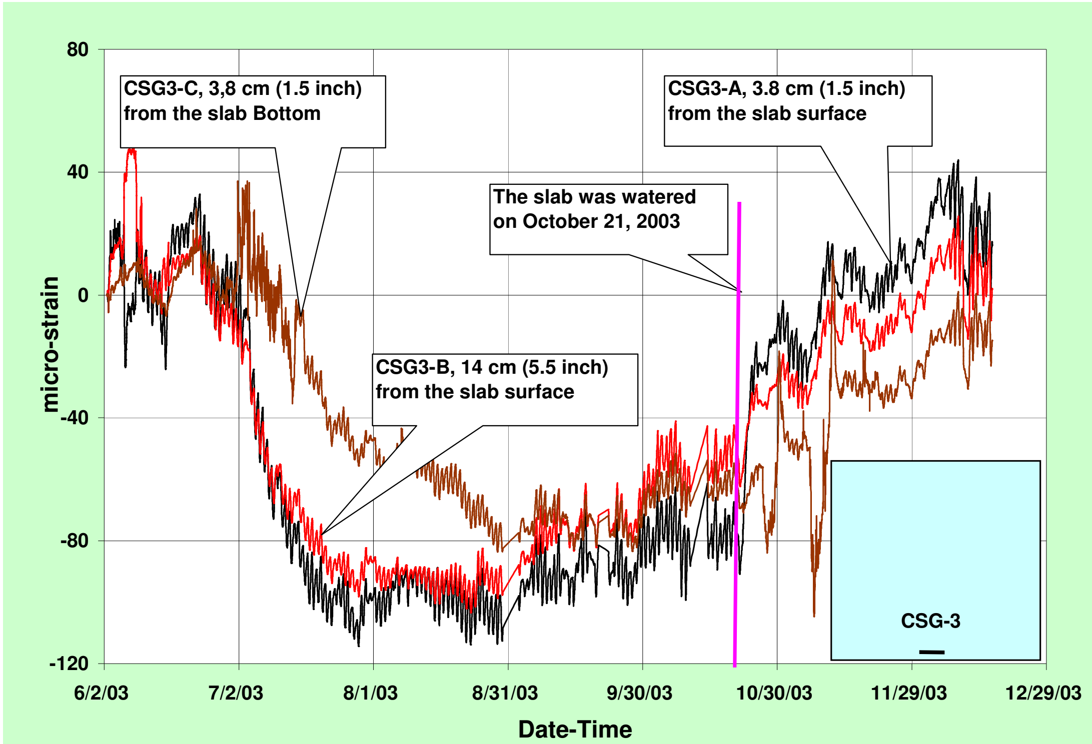


Figure 8. Strain Time History at the Slab Edge

Figures 7 and 8 show the time histories of the recorded strains. All recorded strains developed after the wet curing period. The recorded strain variation reached 150 to 180 micro strains in a month. Considering that the strain gages were located 3.8 cm (1.5 inches) from the surface and bottom of the slab, the maximum strain at surface and bottom would be 206 to 247 micro strains. Strains of these magnitudes would lead to 8.3 to 10.2 MPa (1200 to 1480 psi) stresses if all the strains were stress related. Such high stresses would have cracked the slab. However, no crack was observed during the monitoring. The recorded strains being higher than the critical stress related strain indicates that a large portion of the recorded strains did not produce stresses. A significant relative-movement between the slab and the base was measured by the horizontal displacement sensors and presented in Figure 6. The average length change in the one month period after the wet curing was a shrinkage of 1.1 mm (43 mils). If the two ends had been restricted, the average tensile stress would have been 9.95 MPa (1443 psi) that would also have led to a through transverse crack. The relative movement between the slab and the foundation released the above stress and limited the concrete stress to a value below its tensile strength. Most of the relative movements were caused by moisture rather than temperature changes. The strain gages were not designed to compensate for some non-stress related strains, so they entered the strain record.

All measured strains became relatively stable in daily average in about one month after the wet curing except the strains at the lower strain gage at the south edge of the slab (Figure 8). This gage took about two months to become stable. After the slab was watered on October 21, 2003, all upper strain sensors bounced back. However, after the slab curling at the corners became stable (about one week after the watering started on October 21, 2003), all upper strain gages kept increasing. Or, the "recovery" of strains took a much longer time than the "recovery" of slab curling (Figure 5). This fact indicates that the slab curling and strain responses do not follow a one-to-one relationship. When the measured values of slab curling at a corner were the same, the corresponding strain measurements could be very different. The uncertainty was probably caused by the unknown interface conditions between the slab and the foundation surface. It was also influenced by the nonuniformity and nonlinearity of the relative humidity and temperature in the slab. The observed phenomenon indicates that it has to be considered by any analyst who intends to precisely predict the slab curling and strain responses under environmental variations.

Verification of the Relationship Between Horizontal and Vertical Displacements in a Simple Model

Suprenant presented a paper in two parts, entitled "Why Slabs Curl" with following discussion by R.E. Tobin (Suprenant and Tobin 2002). Tobin suggests using a simple formula to predict vertical curling, Δ, by using the horizontal slab shrinkage parameter S_c – defined as the difference in linear unit shrinkage between the top and bottom of the slab and given by the following equation using the data received from the horizontal deflection sensors (HDs):

$$S_c = \frac{(HD1 + HD3) - (HD2 + HD4)}{L} \times \frac{H}{H'} \tag{1}$$

and

$$\Delta_{Edge} = \frac{Sc \times L^2}{8 \times H} \tag{2}$$

where H and H' are shown in Figure 2 and L is the length (or width) of the slab. If we assume that the slab shrinkage is uniform in all directions, equation (2) can also be used to predict the curling at the corner by replacing the L with the diagonal length of the slab L'. In our case, L' equals to L multiplied by the square root of 2. Therefore, the corner curling deflection is twice the edge curling deflection.

$$\Delta_{Corner} = \frac{Sc \times L^2}{4 \times H} \tag{3}$$

Equations 2 and 3 can also be approximately rewritten as:

$$\Delta_{Edge} = \frac{R \times \theta^2}{2} \tag{4}$$

$$R = \frac{L \times H'}{(HD1 + HD3) - (HD2 + HD4)} = Sc \times H \tag{5}$$

where R is the radius of the sphere and θ is the angle shown in Figure 9. In fact, equations 2 and 3 essentially are the same as the equation presented in (Huang 1992). The only difference is that it is expressed in a different way. If a slab approaches absolute flatness, R will become infinitively large and θ will become infinitively small, and the curling deflection Δ will approach zero.

It should be pointed out that the above equations are derived from the geometrical relationship shown in Figure 9 and ignore a number of the physical characteristics of the structure of the slab. For example, the self-weight effects are not considered in the equations. If the interface between a slab and its foundation is assumed frictionless and the concrete material is assumed linear elastic, a slab curling process may be analyzed in two steps. The first step is governed by the above pure geometrical equations. At the end of the first step, the slab will be curled. At the beginning of the second step, self-weight of the slab is applied and an equilibrium state of the slab may be predicted by an appropriate tool such as a finite element method with iteration procedure. Both 2D and 3D finite element programs (such as JSLAB2004 and ISLAB2000 (2D) and NIKE3D) may have the above capability. However, the one-to-one relationships between environmental factors (temperature and moisture variations) and slab responses, and/or between the slab displacement and stress responses do not exist in the measurements of the single slab test that is simpler than any real pavement analysis. Therefore, the results calculated by any program need to be carefully analyzed before application.

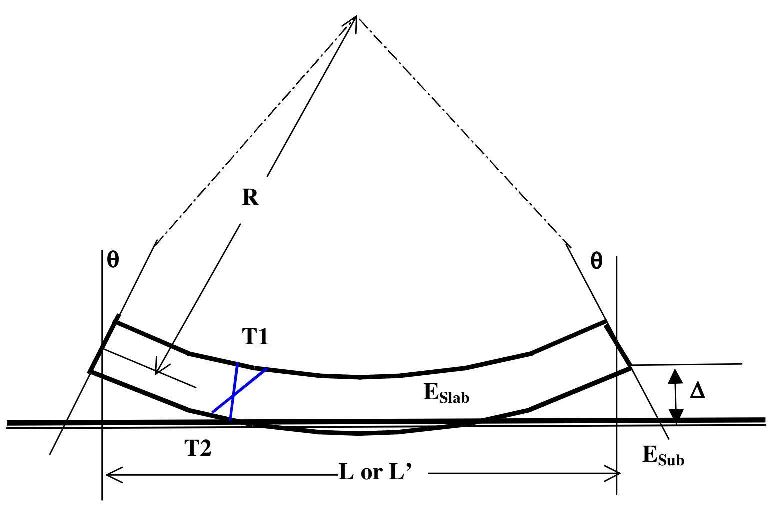


Figure 9. Simple Model for Curling Analysis

Since the vertical deflections at the corners and edge, and the horizontal deflections at two middle points of slab edges have been independently measured, it is interesting to compare the measured relationship between the horizontal and vertical displacements with those listed in the above equations.

Figure 10 presents the comparisons of the edge and corner curling deflections directly measured to those predicted by Equations 2 or 3. In the first month after the slab wet curing, the measured curling deflections were very close to those predicted by HDs using equations 2 and 3, though these equations consider neither the effects of self-weight nor the effects of interface characteristics. In the following months, even though the two curves were sometimes closer and sometimes not, the trends of daily variations were always very close.

Verification of Slab Curling By Profile Measurements

Profiles were continuously measured every working day on the north edge of the test slab (Figure 2) by using an FAA developed profiler and software. The equipment moves on a long beam crossing the entire slab edge length, and consists of a Selcom infrared laser unit for vertical displacement, an incremental rotary encoder, a data acquisition box and a laptop PC (Marsey and Dong 2004). The dots in Figure 11 show the difference between the reading in the middle of the profile (at the point VD2) and the average of readings at the two ends (at the points VD1 and VD3). They may be defined as "the movements of the north edge center (corresponding to the location of VD2) relative to the two corners (corresponding to the locations of VD1 and VD3)". Since the VD3 sensor had a problem shortly after installation, (VD1-VD2) and (VD1+VD4+VD5)/3 – VD2 are presented in Figure 11 to compare with the quantity measured by the profiler. In about a two month period after the slab wet curing starting from July 2, 2003, the results measured by the VDs and by the profiler were comparable. This verifies the reliability of the VD measurements.

Conclusions

The data received in the monitoring project show that the maximum slab curling reached a very high level even though the slab was subjected to a full month of wet curing. The observed slab in-plane and out-of-plane movements were very complicated. However, their relationship can be roughly described by a very simple equation. Their behaviors (curling up and curling back) were also very different for a completely wet slab exposed to the indoor environment and for a dried slab under manual surface watering. Comparisons of corner curling, temperature and relative humidity data indicate that the long-term corner curling was primarily caused by relative humidity variation rather than by temperature variation. The test data also shows that a significant portion of measured strains were not stress related. Recognizing this fact it is necessary to correctly read the strain data recorded over a long period. Another important finding is that the one-to-one relationships exist neither between environmental variations (temperature and moisture) and the slab responses (displacements and strains), nor between the slab curling and the strains in the slab under the environmental variations. The last two observations were caused by multiple factors, including concrete creep, the uncertainty of slab-base interface interaction, the nonlinear variations of the temperature and moisture in the slabs. Therefore, long-term simulation of slab effective strains still has a long way to go.

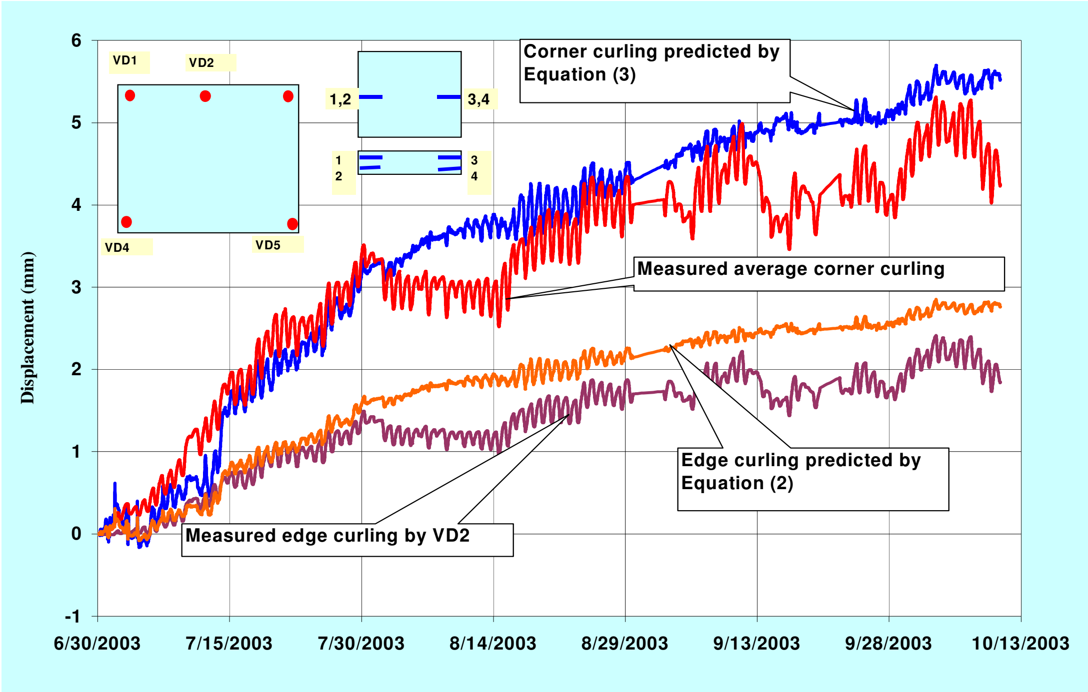


Figure 10. Measured and Predicted Corner and Edge Curling

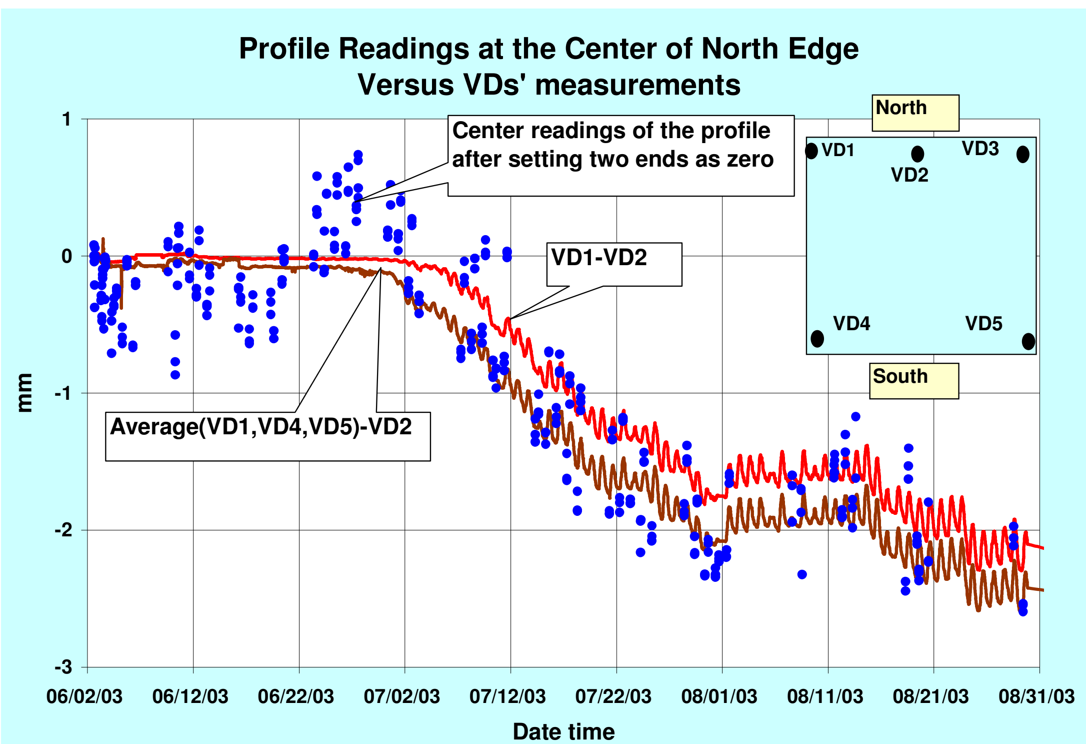


Figure 11. Verification of the Measured Curling by Profile Measurement

Acknowledgments

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